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A PROGRESS REPORT ON THE DEVELOPMENT OF A CONTAINMENT VESSEL AND DEWAR FOR THE PARTICLE ASTROPHYSICS MAGNET FACILITY (ASTROMAG)

PREPARED FOR:
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1.0 Background:

The ASTROMAG facility is the heart of a large charged particle detection and resolution system. This ASTROMAG system utilizes a superconducting magnet consisting of a large superconducting magnet coil with a stored magnetic energy of approximately 15 MJ. The active coil will have a mass of 1200 kg. This magnet will be cooled by a cryostat using a liquid helium dewar for storage. The cryostat will have a series of gas-cooled shields with an external guard vacuum shield and an internal dewar. The magnet and cryostat will be designed for shuttle or Delta launch and will be designed to withstand the internal pressure of expanded helium under full quench conditions when venting is prevented.

The external guard vacuum shell is required to maintain a vacuum for earth based testing and for cold launch of the cryostat and magnet. The magnet is designed to operate at 4.4 degrees Kelvin with a peak field of 7.0 tesla. The superconducting material within the magnet is niobium titanium in a conductive matrix.

1.1 Purpose of Present Study:

The present study is directed toward development of the cryostat containment vessel, guard shield development and dewar support system. As part of the ASTROMAG facility development team the Catholic University school of engineering has directed its efforts toward development of the structural and mechanical support elements within the ASTROMAG facility. These efforts include development of trade-off studies aimed at optimizing the performance of critical elements of the structural support system. These elements include:

1. Development of designs for a Dewar system
2. Design of the Dewar support straps
3. Development of a Vacuum Guard shell assembly
4. Preparation of geometry studies to support experiments
5. Structural analysis of Launch landing and related loads for the facility.

As part of this study, the present effort has been directed toward evaluation of the cryostat dewar and its support assembly for shuttle launch requirements.

2.0 The Catholic University Proposed Design Concept

Figure-1 shows the proposed arrangement for the ASTROMAG facility as developed at the Catholic University school of engineering. This figure shows the arrangement of the cryogen tank housed within its outer cylindrical guard vacuum shell with two concave end caps. This outer guard vessel is assembled from two cylindrical sections each of which is subtended from a central ring flange. These ring flanges have an metal "O" ring gland and form the vacuum seal for the vacuum guard.

The two cylindrical sections are slightly different in that one of the two sections also has a "channel" shaped ring section which in turn supports a series of radial "boss" supports. These bosses provide anchors for the internal dewar support straps.

The penetrations for the support straps are shown in figure-2. Each penetration is adjustable from the outside of the vessel without breaking the vacuum seal. This is accomplished by means of a metal bellows structure which is attached to the support boss as shown in figure 2. The type of metal ring seal between the two supporting flanges is shown also in figure 3. The flanges (see figure-1) are bolted together by a series of high strength tie bolts which are pre-loaded to 60% of their yield strength and which are provided with a locking feature to prevent "back-off" of torque during the launch environment.

Notice also that one of the two cylindrical shell sections is used to assemble the cryogen tank and magnet in place within the assembly while the second shell simply acts as a passive cap. This facilitates alignment and assembly of the cryogen and magnet.

The guard vessel has a number of interface attachment pads for instrument mounting points. The shell structure provides a surface for mounting an "antiproton" experiment and a "isotope" experiment.

The ends of the guard vessel are dished in-ward to provide close proximity of the experiments to the magnet and to minimize the weight and thickness of the end caps.

The dewar and magnets are supported by means of 12 radial ties tangent to the dewar and attached to the guard shell "C" ring. The magnet coil is supported by means of a series of thermal isolator brackets on the cryogen tank. These brackets are fabricated from an isolator material such as fiberglass of KEVLAR.

A series of vapor cooled shrouds are sandwiched between the dewar cryogen tank and the outer guard vessel. These shrouds are attached to the support isolators and are thermally coupled to the vapor exhaust (not shown) from the cryogen tank.

A cryogen pump mounted to the outside of the guard shell structure has a "cold finger" which maintains the temperature of the outer-most vapor cooled shield to a reasonable temperature.

The dimensions of the outer shell are nominally 235 cm in diameter and 273 cm in length.

2.1 Finite Element Model

A preliminary NASTRAN finite element model of the dewar and cryogen tank have been prepared and plots of these models are shown in figure-3. The top assembly (ie., figure 3 a) shows the integrated overall model while figure 3b and 3c show the guard vessel and the dewar models.

3.0 Structural Requirements

The ASTROMAG experiment must be designed to meet not only the physics requirements but it must also meet the requirements for shuttle interface, space station interface and related environmental requirements. Table-1 lists the general implied requirements for each of these interfaces.

The shuttle mechanical interface will be by means of a shuttle/astromag interface retention system. Figure 4 shows the general dimensions of the shuttle cargo bay while figure 5 shows the arrangement of the retention system reactions in the bay. There will be 5 support attachment points. (ie, 4 sill fitting attachments and 1 keel attachment point). The two forward sill fittings will react x and z direction reactions , the aft two fittings will react z direction reactions and the keel will react y direction reactions. The interface space truss has not been configured for this experiment but is part of the proposed Catholic University design project.

3.1 Geometry of Magnet

The dimensions of the magnet used for this study are shown in figure 6. These dimensions were supplied by the experimenters and were used as a base line for the geometry of the support vessels.

4.0 Safety Requirements:

The experiment will have to demonstrate the structural integrity of the cryogen tank under expected "quench" conditions in which the thermal heat from the quench is used to "boil-off" helium within the tank. This helium will build up pressure and will produce this internal pressure within the cryogen tank. There will be a need to develop an analysis of the tank which will show that the tank would "leak before it would rupture". The tank will also have to be proof tested to a pressure sufficient to insure an adequate margin of safety against rupture.

This would most likely be tested to 1.5 times the expected internal pressure.

The external guard vessel will be designed so that it will relieve internal pressure through a pressure relief system in the event that such pressures develope. The guard vessel, will be designed for 1 atmosphere of external hydrostatic pressure and will be analyzed for a design "over pressure" of 1.5 times that amount (ie., 22.5 psig).

4.1 Fracture Control

There will be a need to develop a fracture control plan for the experiment and a supporting test and inspection program for elements of the system including:

1. pressure vessel materials
2. guard vessel materials
3. Support retention materials
4. Support straps.

The system will be analyzed such that the components will be evaluated for potential brittle fracture by evaluating their material fracture toughness and relating these to the crack growth of pre-determined crack sizes in the materials. The requirements for such evaluation and inspections are given in table -2 , 3 and 4 as well as figures 7 and 8. The general materials will be selected and inspected to assure non-propagating cracks or to assure that crack growth, if it occurs, will be acceptable during the fatigue life of lift off, landing and test load cycles (times 4).

This design approach is indicated in figure-9 attached. The regions 1 or 2 of figure 9 will be used for this design.

5.0 Materials Used

The present study will evaluate the potential for using composite material construction as well as aluminum materials for the guard vessel, the vacuum vessel and support straps. The potential benefits of composite materials such as Dupont's Kevlar will be evaluated for the cryogen tank . There will be a need to evaluate the thermal and structural performance of these materials. The types of metallic materials shown in figure 10 will also be evaluated. The materials which provide superior strength at low temperatures such as aluminum will be evaluated. Table 6 shows potential candidate materials for the primary metallic structures. These same elements could also be fabricated from Kevlar 49 Aramid fiber materials.

6.0 Analysis:

The experiment will have to be evaluated for its structural integrity under launch load environments. Since the structure will be subjected to a number of loads and thermal stresses at launch and abort landing conditions, there will be a need to evaluate these combinations of loads and stresses. The final qualification of the structure will be by analysis rather than by test. The project will validate all models by test correlation and will develop validated models for the final qualification.

Table 7 shows the type of analysis and tests which will be required for this effort. This will include random loads analysis, dynamic simulation of lift off and landing loads as well as studies of structural materials required for the experiment. A typical random input power spectral density profile for this type of experiment is shown in figure-11.

7.0 Study Design Goals

The ultimate goal of this design study is to develop concepts and guidelines for the design of the structural support elements. This effort will assure that the minimum weight design will be met with a structure that has the necessary structural integrity and stiffness requirements. The fundamental frequency of the system will be maintained above 20 hz and therefore will not couple with the fundamental shuttle modes.

These design goals can be met if the table 8 guides are met. These design guides are illustrated in the figure 12. As part of this design, the system will be evaluated for lift-off impact loading of a partially filled cryogen tank. These impact loads will also be used for design of the tanks baffles. (see fig 13 and 14).

8.0 Optimize Shell Weight

Each shell will be designed to take advantage of materials and optimal shell geometry properties. The differential expansions, offset reactions due to flange attachments and the different geometric expansion factors at transition sections will all be evaluated for each shell. Figures 15, 16 and 17 illustrate some of these general guides to the design.

9.0 Weight of the System

Based upon a preliminary analysis of the launch loads and forces, the total estimated weight of the system proposed is estimated at 3810 Kg. This weight includes 790 Kg of helium. Table 9 provides a summary of the weight distribution.

10. Work Proposed for Next Phase of the Contract;

During the last half of this contract, a study will be made of the internal forces and stresses within the pressure vessel as a result of full quench of the magnet. This study will determine the requirements for the materials and for the proof test levels for this experiment cryogen tank. In addition, there will be an evaluation of the alternate launch configuration for a launch on board a Delta launch vehicle (see figure - 18).

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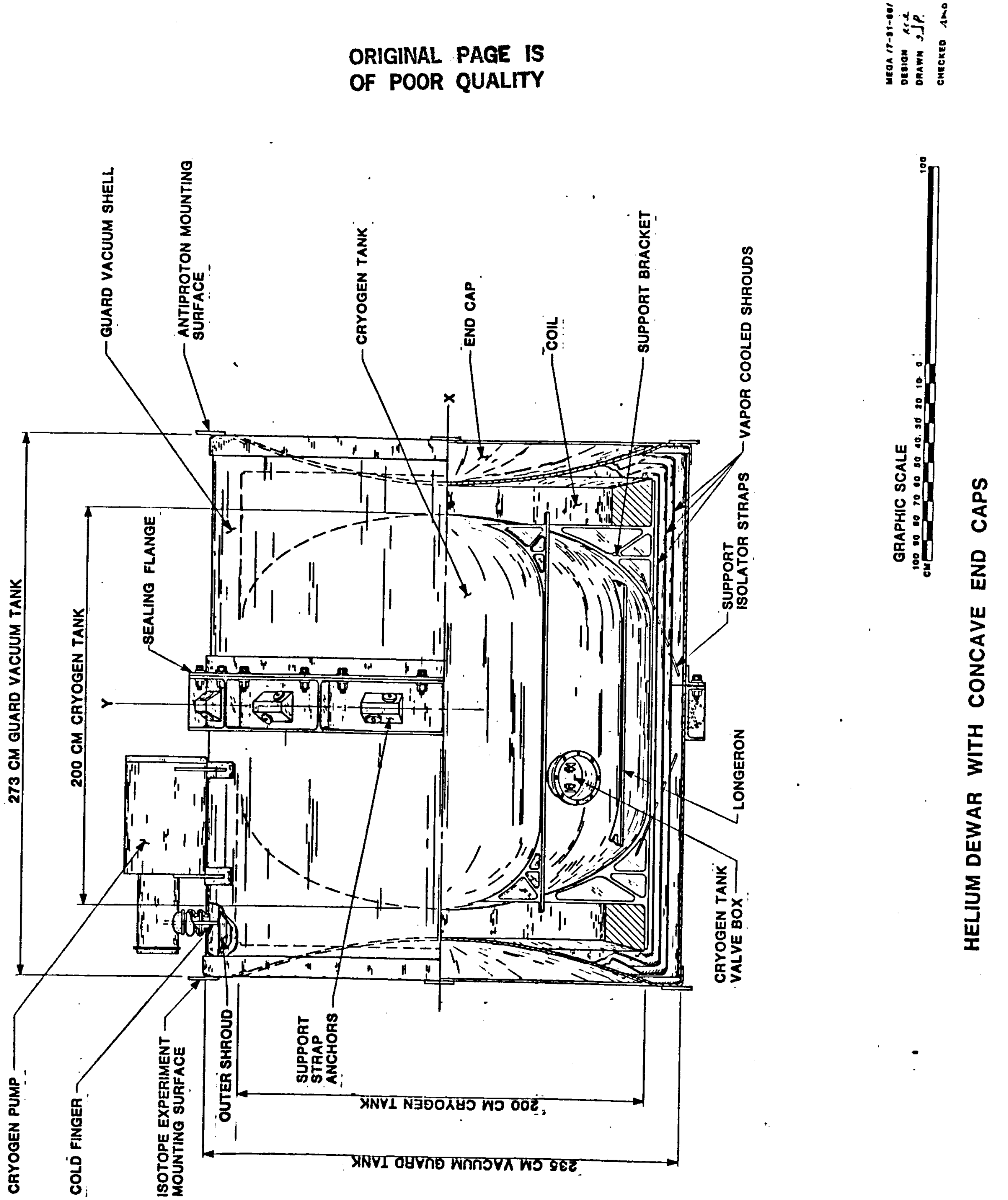
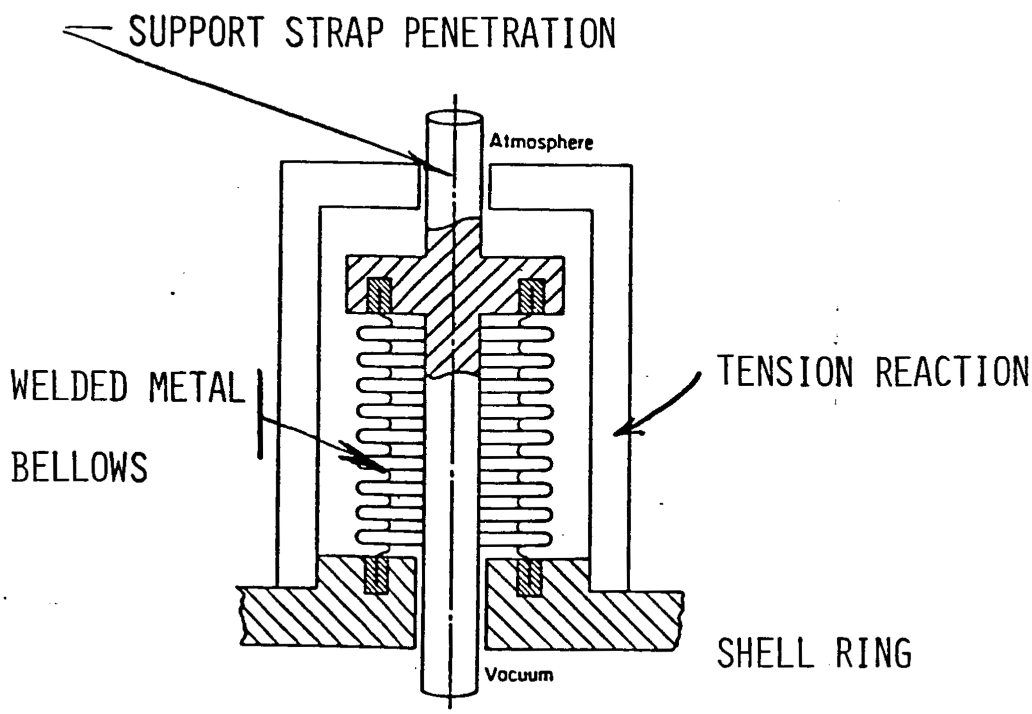
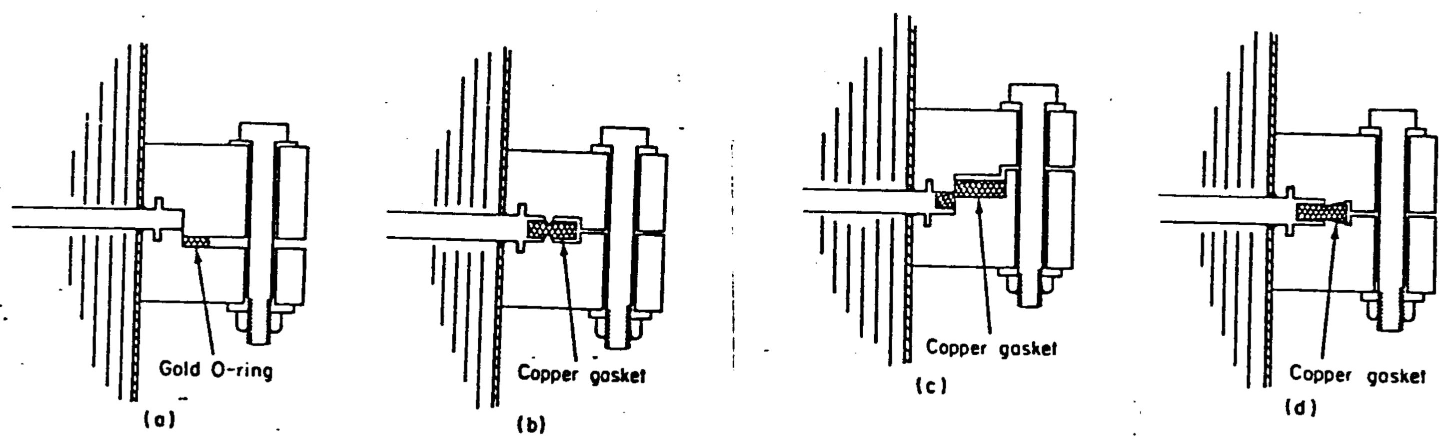


Figure - 1



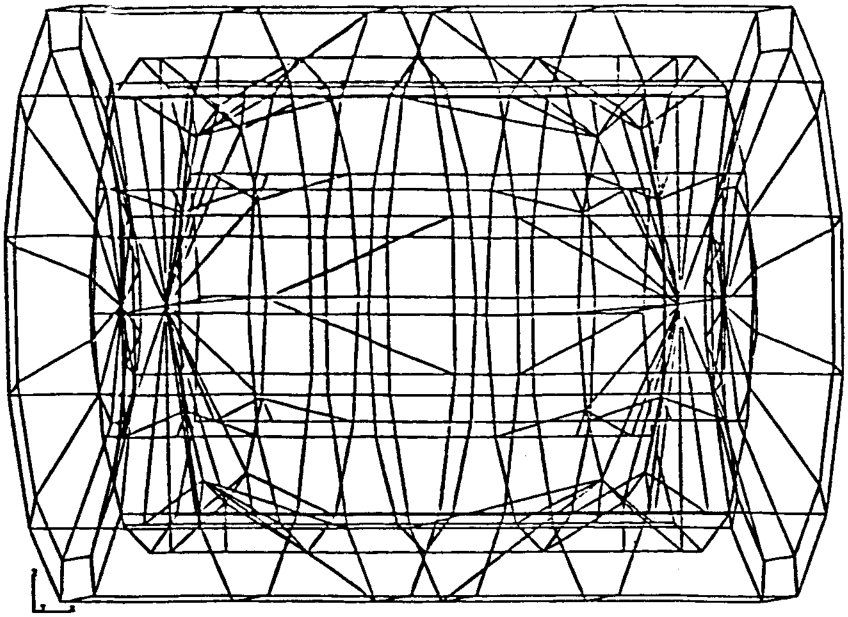
SUPPORT STRAP ADJUSTMENT PENETRATION



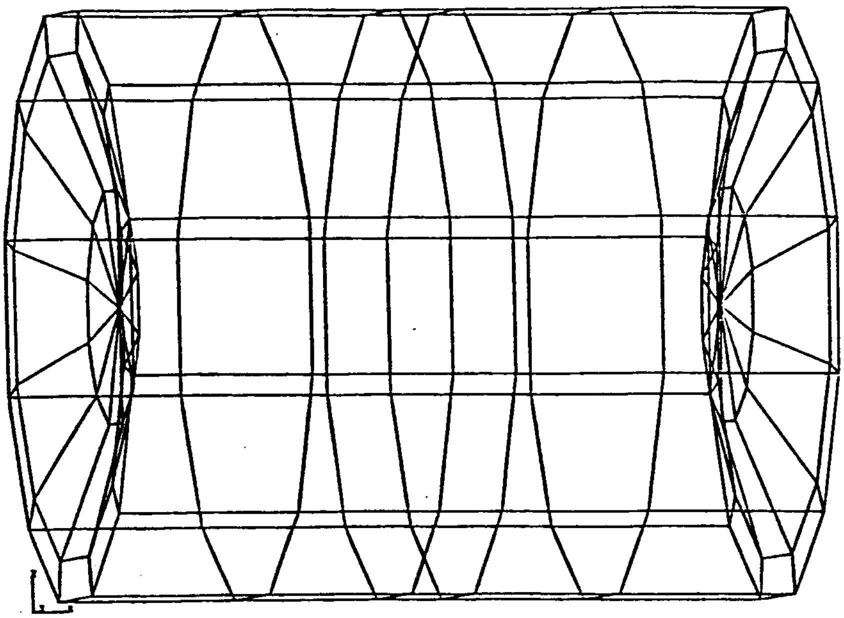
SHELL VACUUM SEAL ARRANGEMENT

Figure - 2

DEWAR
PRELIMINARY NASTRAN MODEL



VACUUM CHAMBER SUBASSEMBLY



CRYOGEN TANK SUBASSEMBLY

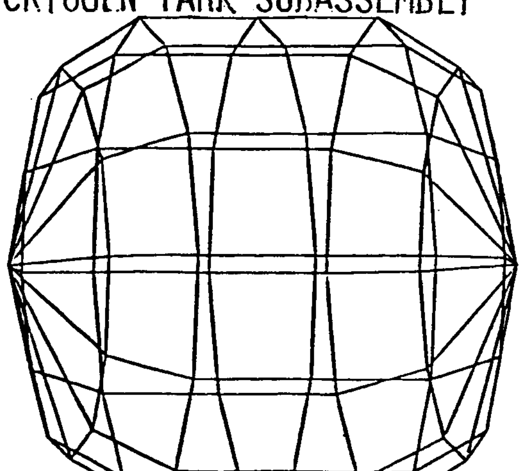
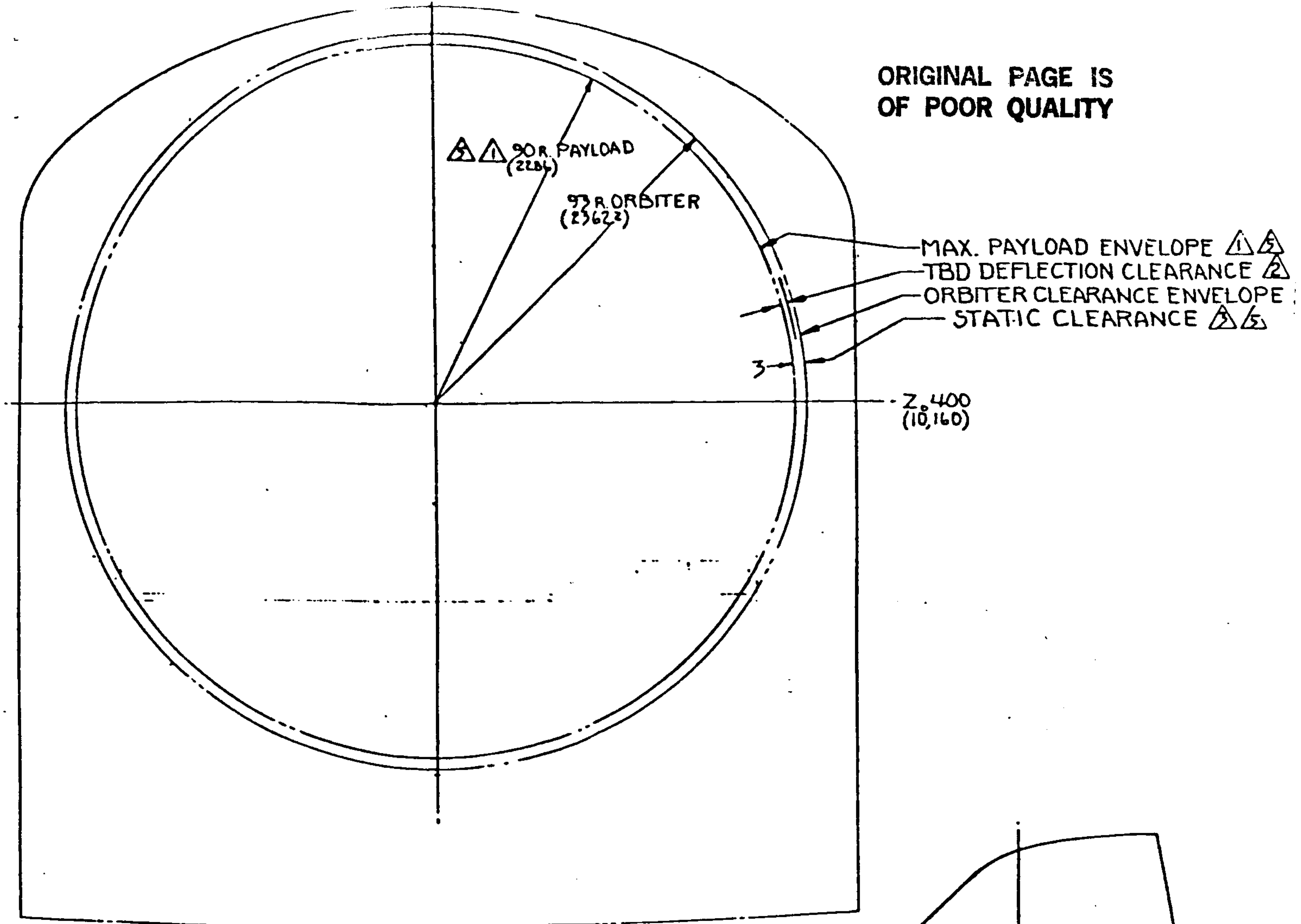


Figure - 3



BASIC MID FUSELAGE SECTION
STATIC INSTALLATION
SCALE 1/20

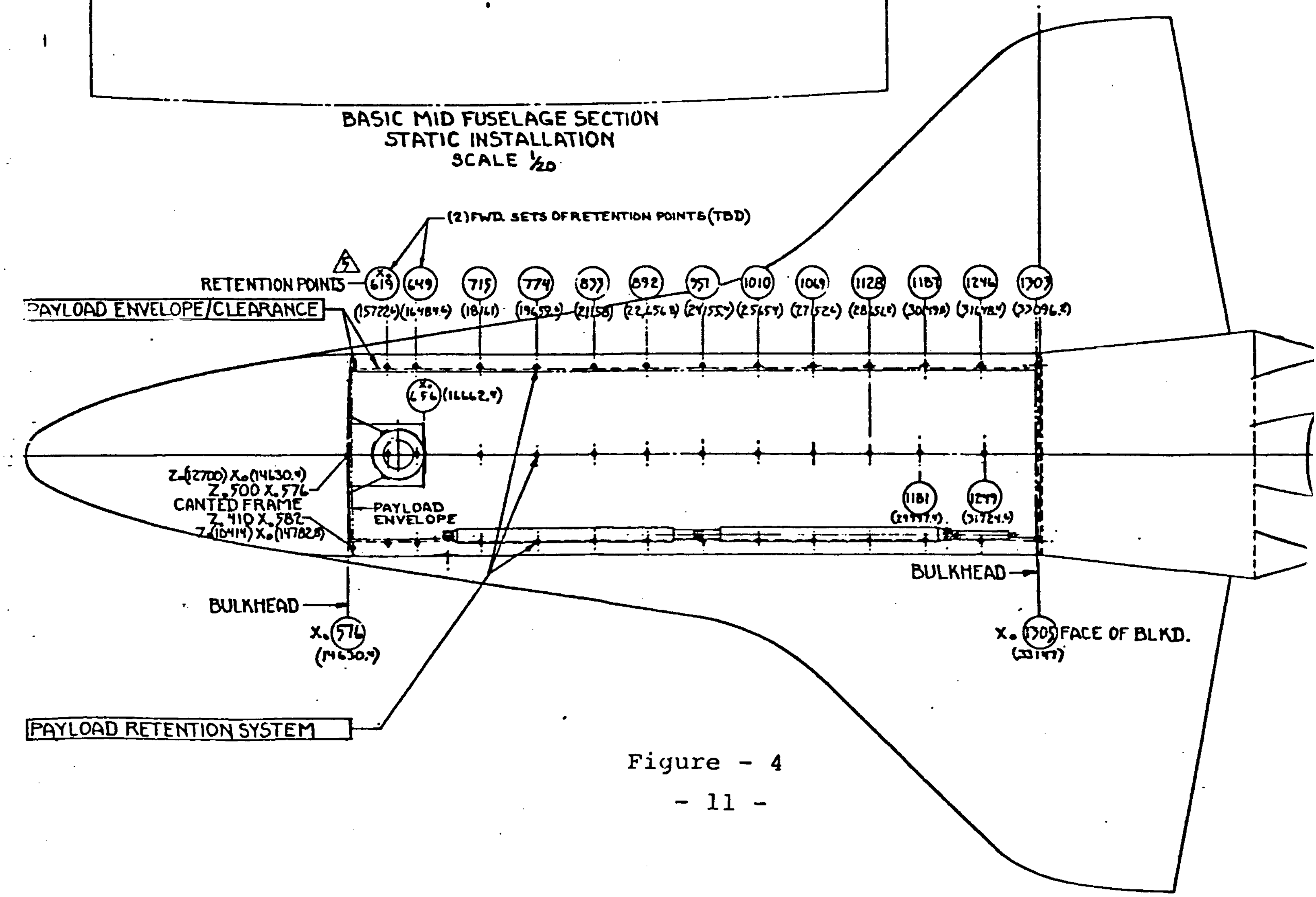
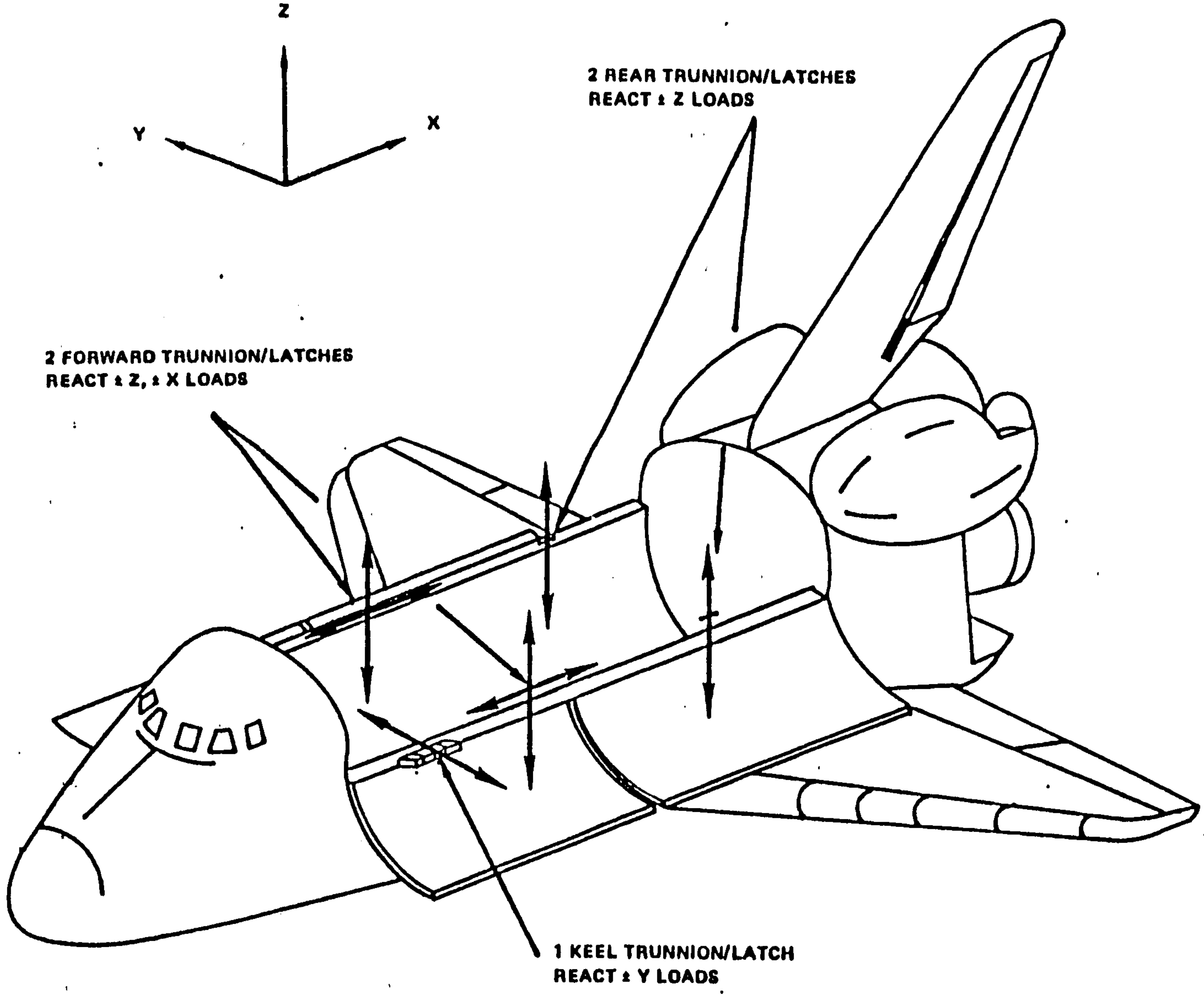


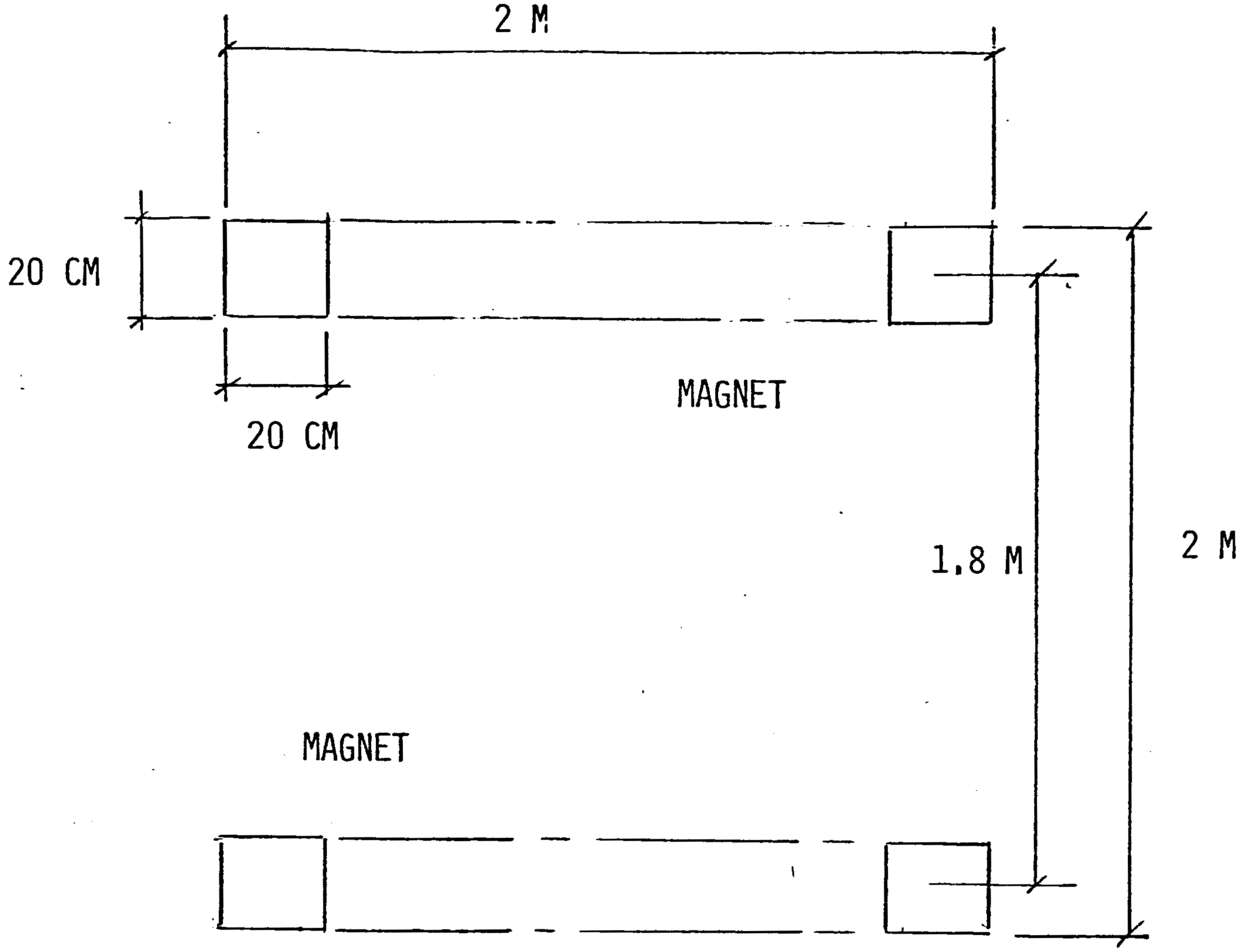
Figure - 4

SHUTTLE RETENTION CONCEPT



Five-Point Retention Diagram

Figure - 5



GEOMETRY USED FOR CONFIGURATION STUDY

Figure - 6

FRACTURE CRITICAL PART SELECTION LOGIC

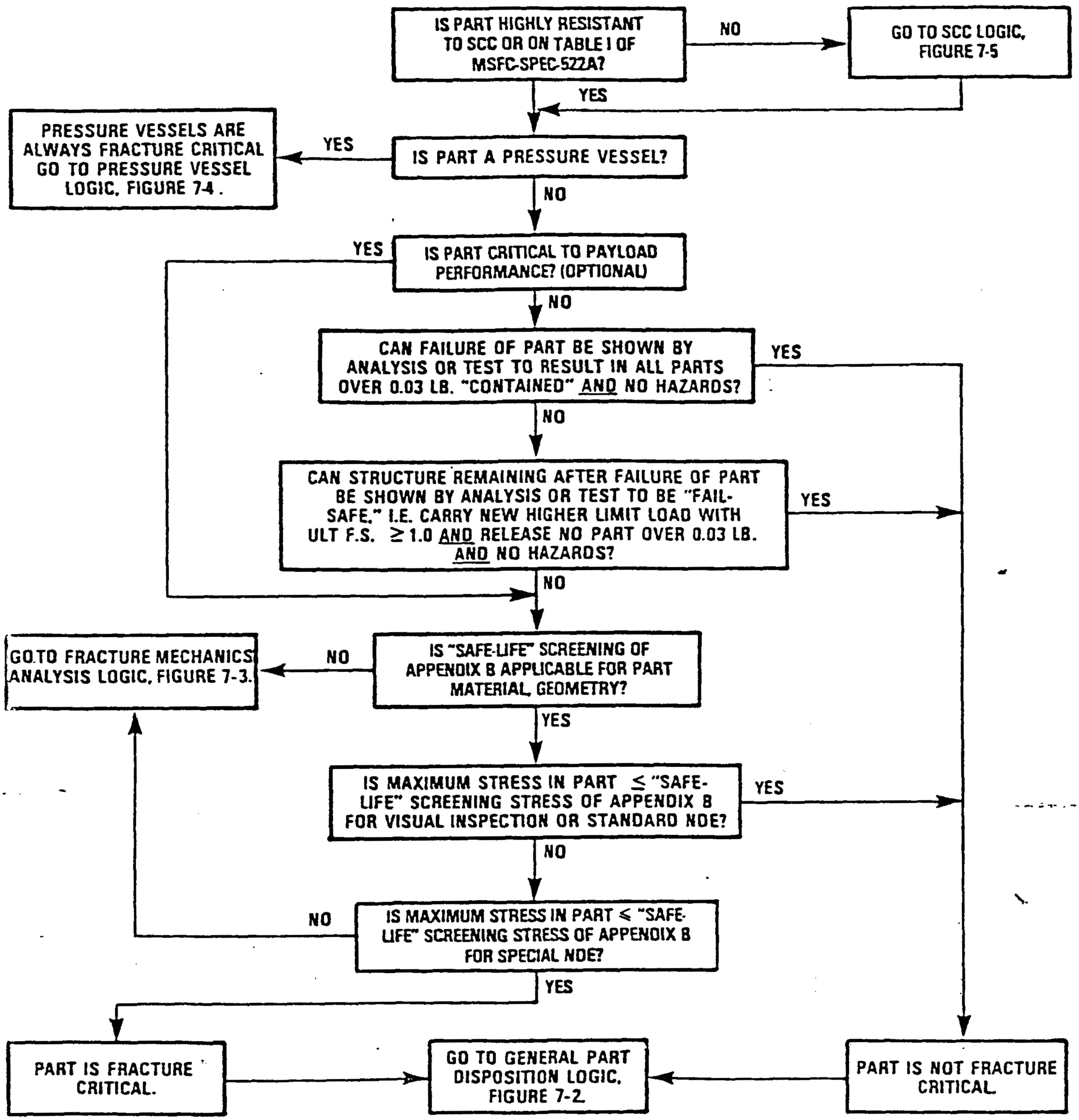


Figure - 7

PRESSURE VESSEL FRACTURE MECHANICS ANALYSIS REQUIREMENTS LOGIC

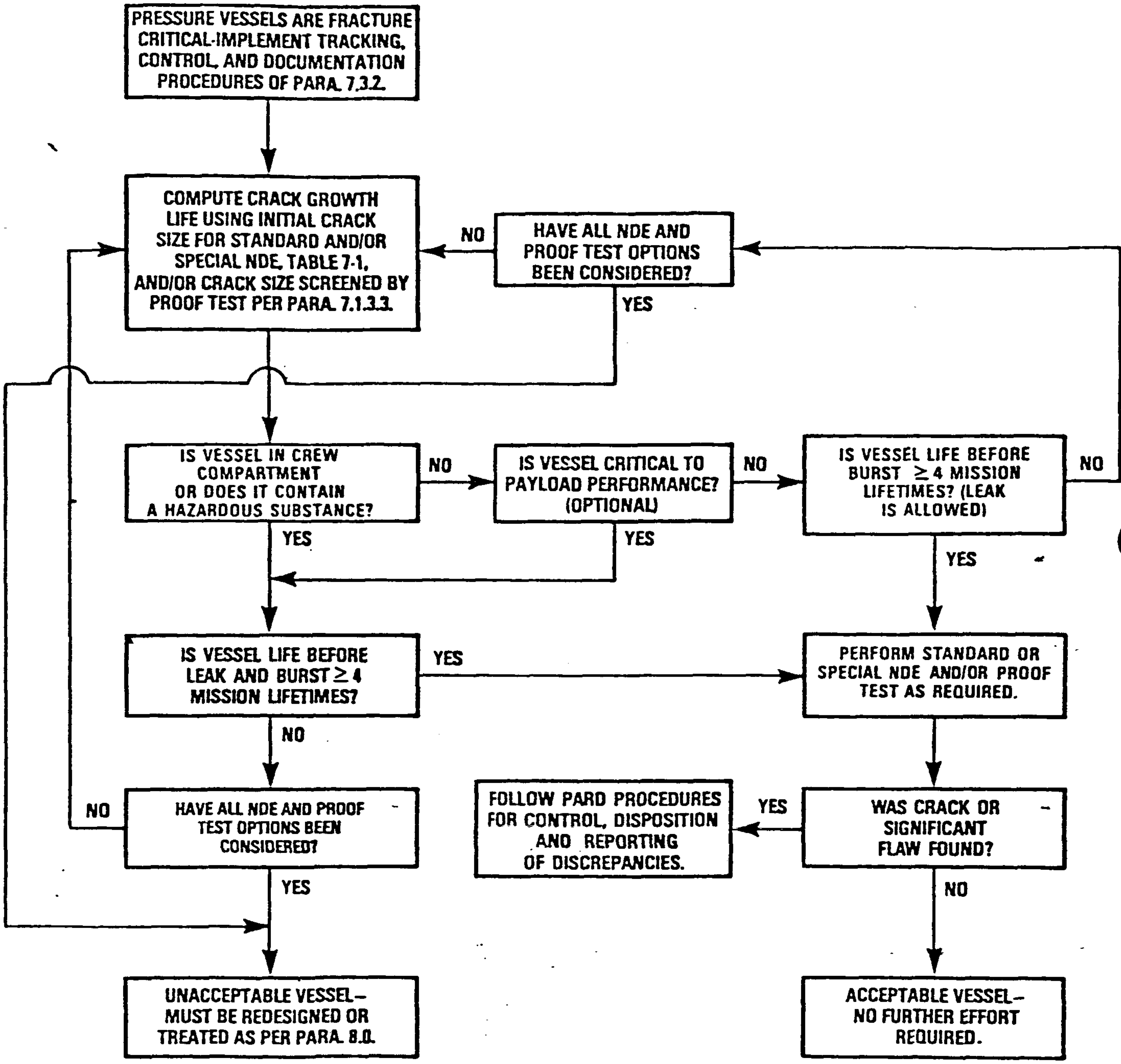
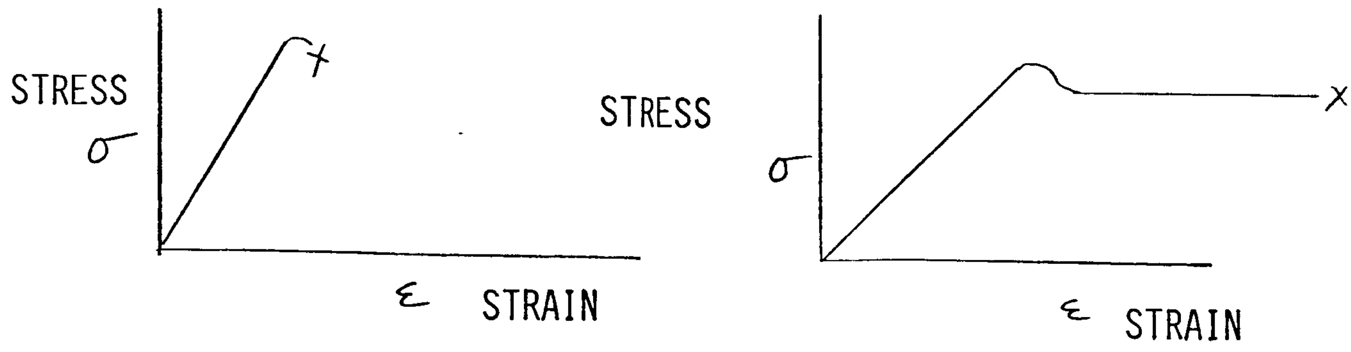


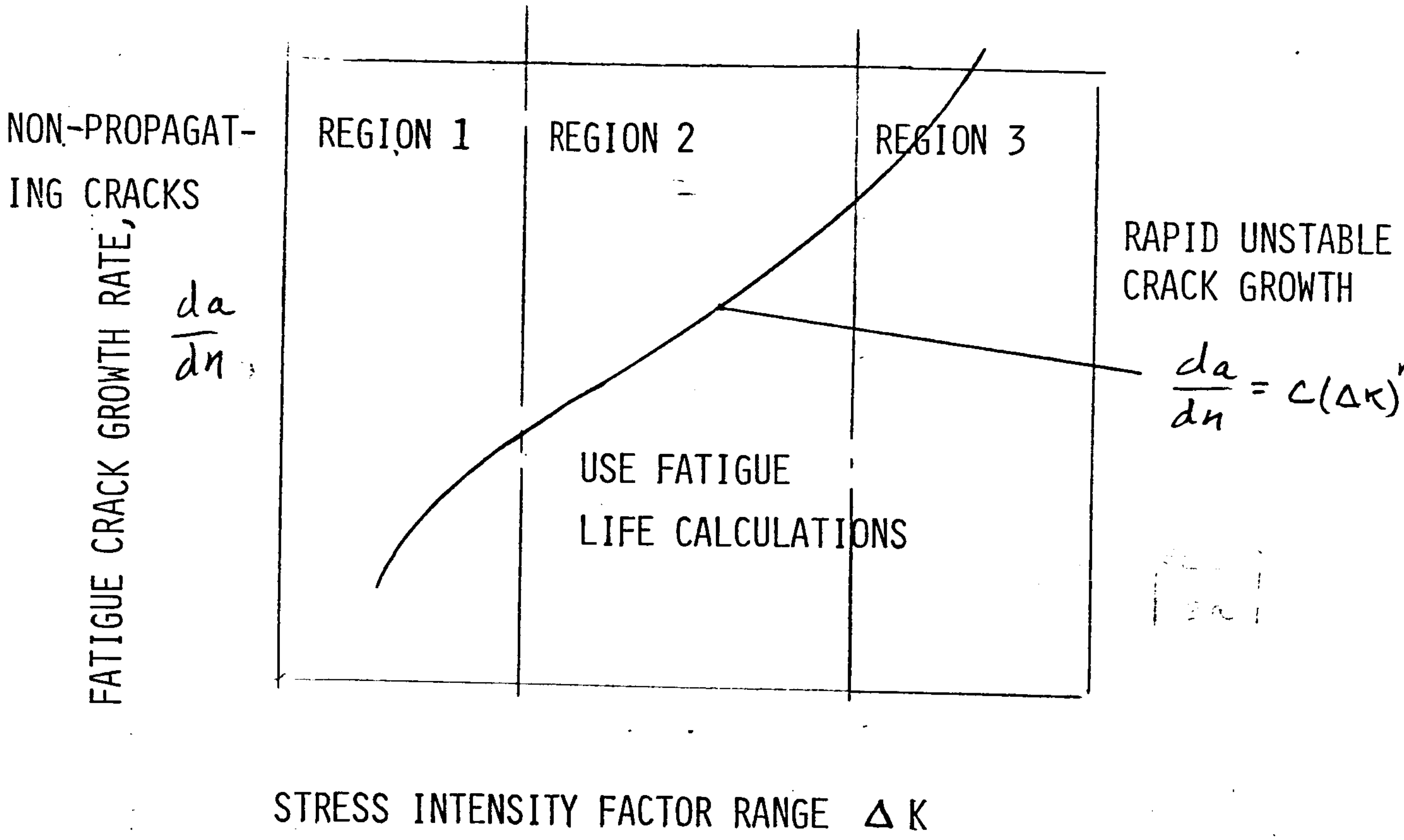
Figure - 8

USE MATERIALS WITH GOOD DUCTILITY AT LOW TEMPERATURES



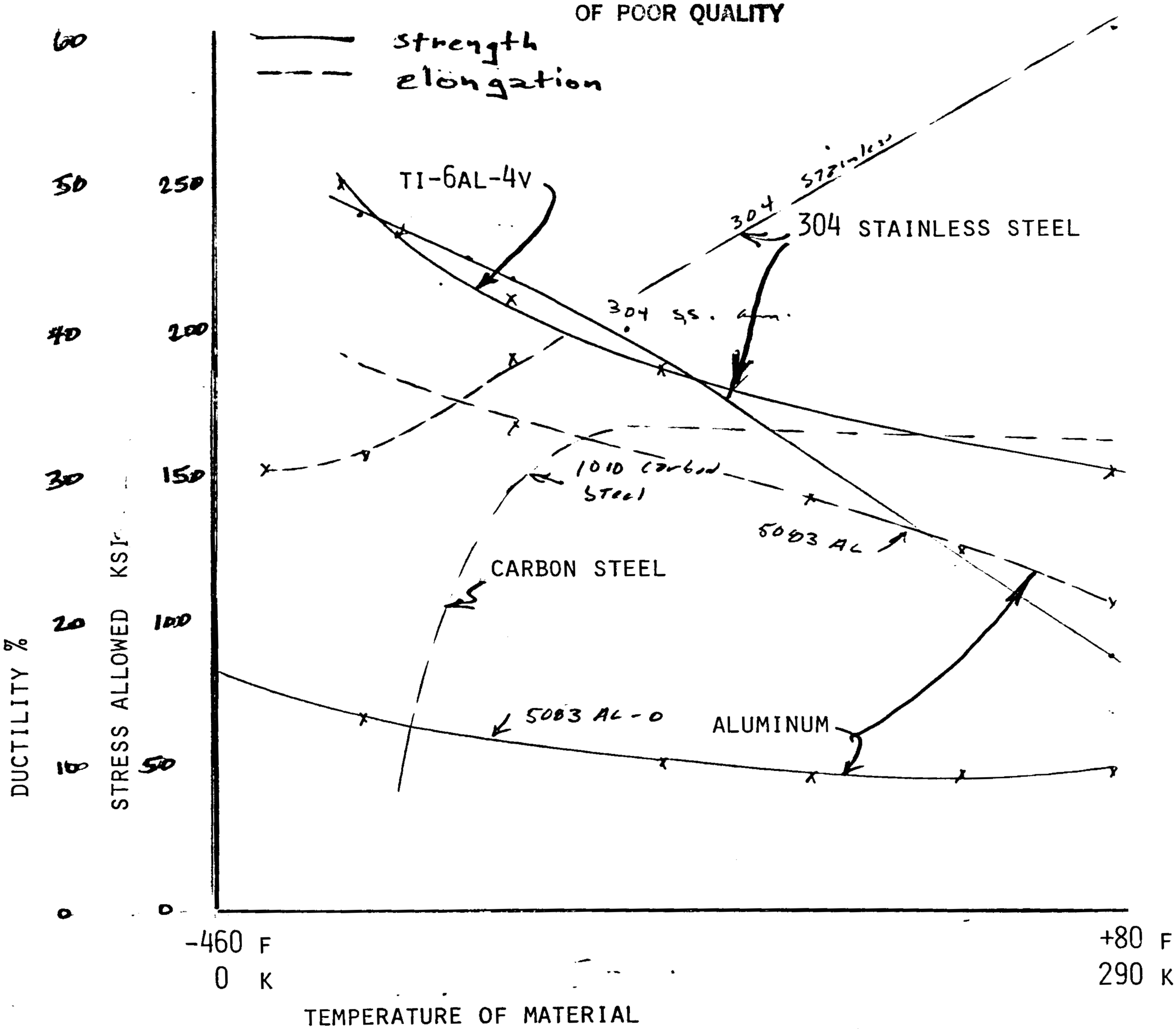
AVOID BRITTLE MATERIALS

USE MATERIALS WITH DUCTILITY



UTILIZE FLAW GROWTH ANALYSIS TO MINIMIZE WEIGHT

Figure - 9



STRENGTH MAY INCREASE FOR SOME MATERIALS, THE DUCTILITY WILL DECREASE FOR LOW TEMPERATURES IN SOME MATERIALS

Figure - 10

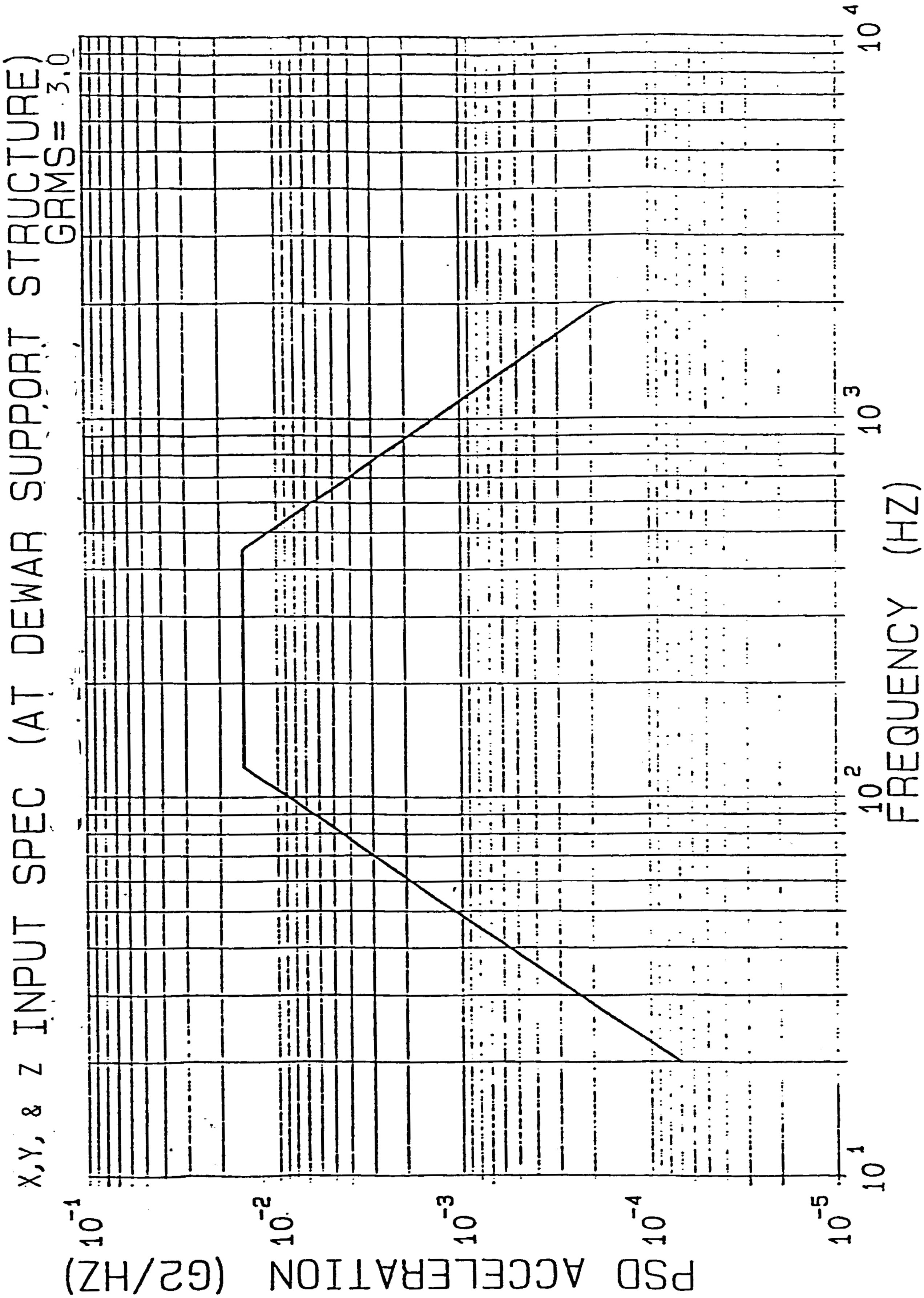
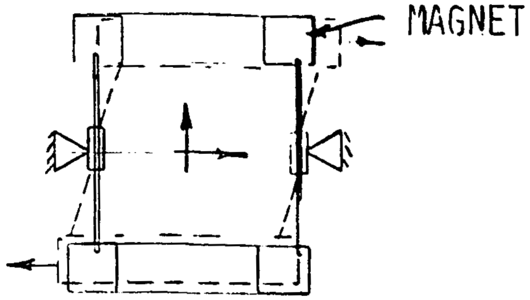
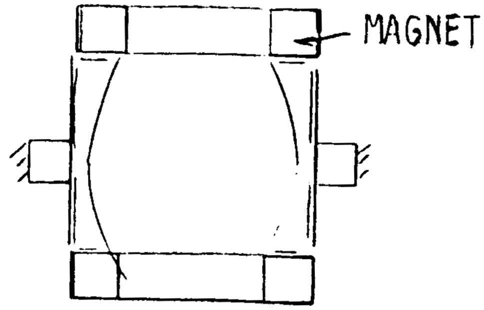

X,Y, & Z INPUT SPEC (AT DEWAR SUPPORT STRUCTURE)
GRMS= 3.0
FREQUENCY (HZ)
10^1
10^2
10^3
10^4
PSD ACCELERATION (G2/HZ)
10^-1
10^-2
10^-3
10^-4
10^-5

Figure - 11

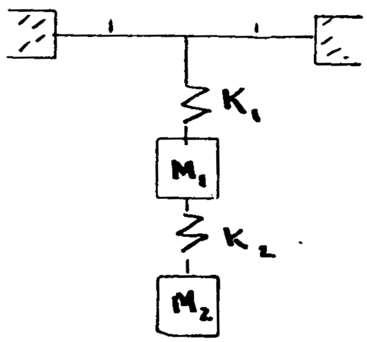
AVOID LOW FREQUENCIES



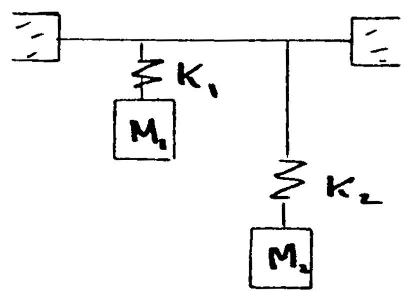
AVOID SOFT LATERAL SUPPORT



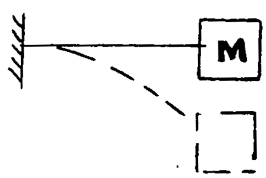
USE SHEAR BRACKETS



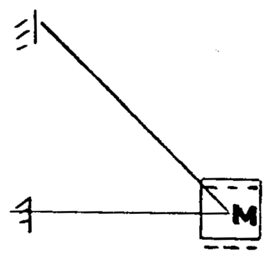
AVOID COUPLED RESPONSE



PROVIDE DIRECT LOAD PATHS



AVOID FLEXURAL SUPPORTS



PROVIDE AXIAL AND SHEAR LOAD PATHS

Figure - 12

TYPICAL SLOSHING MODES IN SPHERICAL TANKS

DEFINITION OF WAVE MODES

SPHERICAL TANK INVESTIGATION

CATEGORY

STANDING

STANDING COMBINED WITH LATERAL AND VERTICAL LIQUID MOVEMENTS

BREAKING

SWIRLING

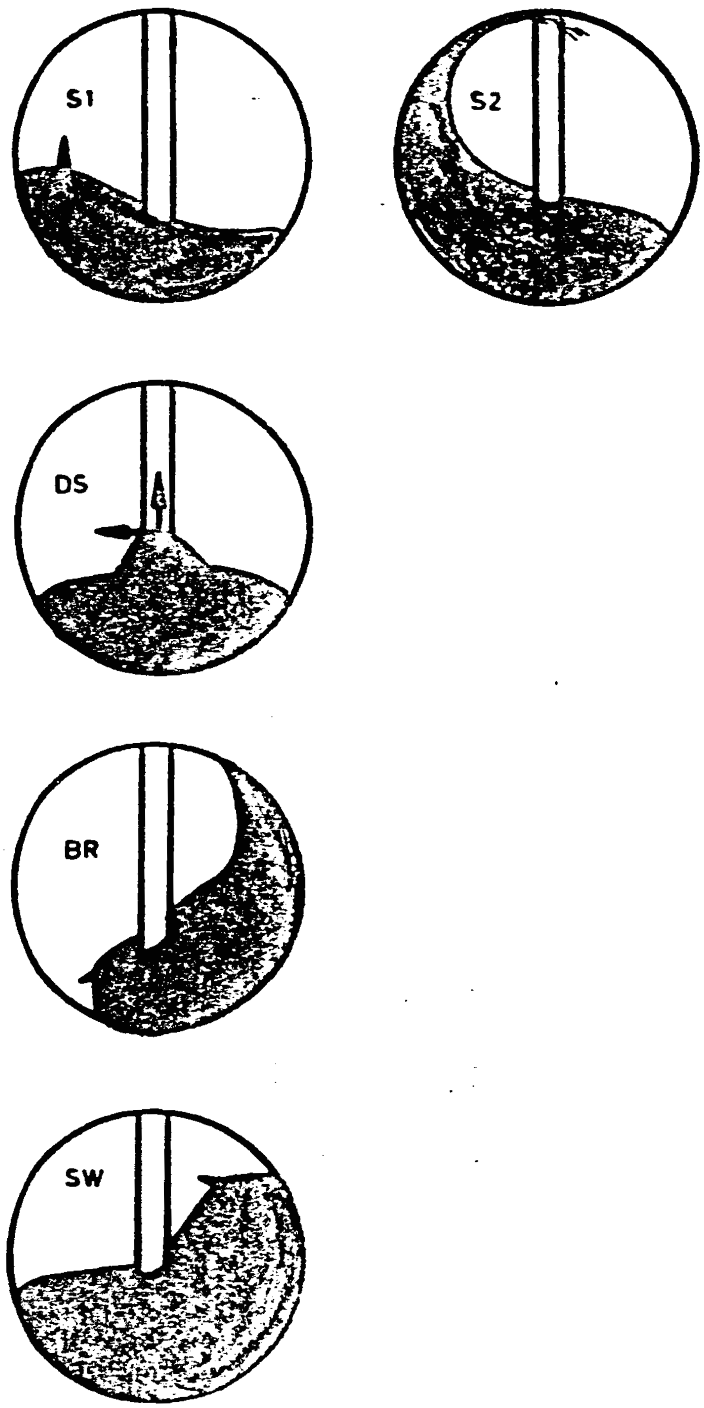
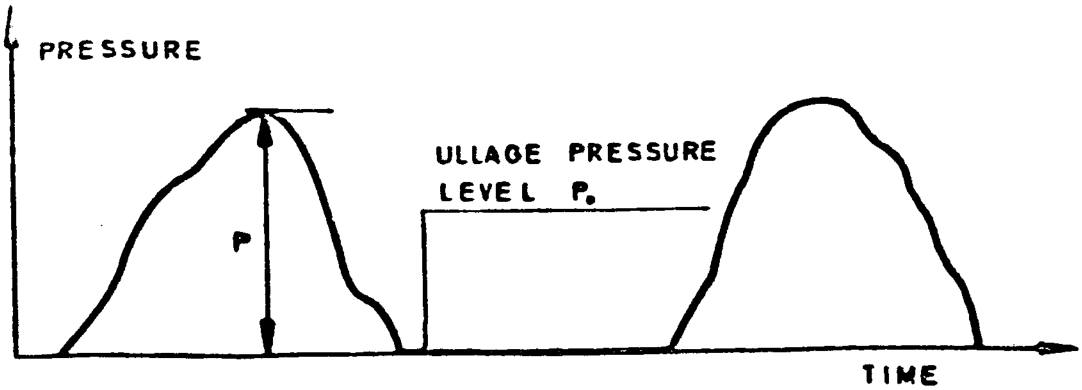
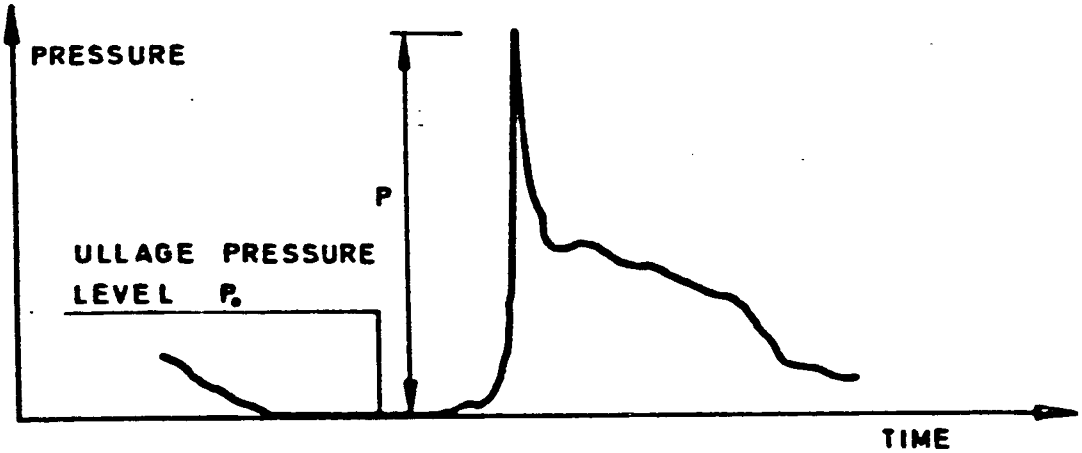


Figure - 13

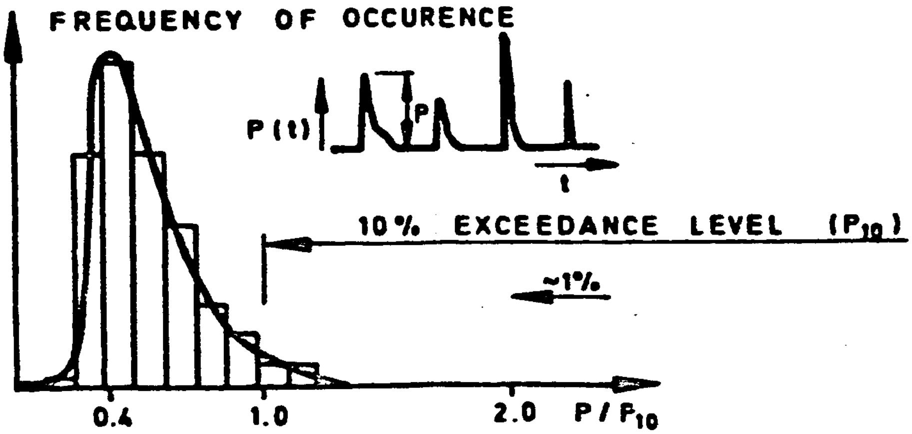
TYPES OF DYNAMIC LOADS CAUSED BY SLOSHING



(a) NON-IMPULSIVE PRESSURE



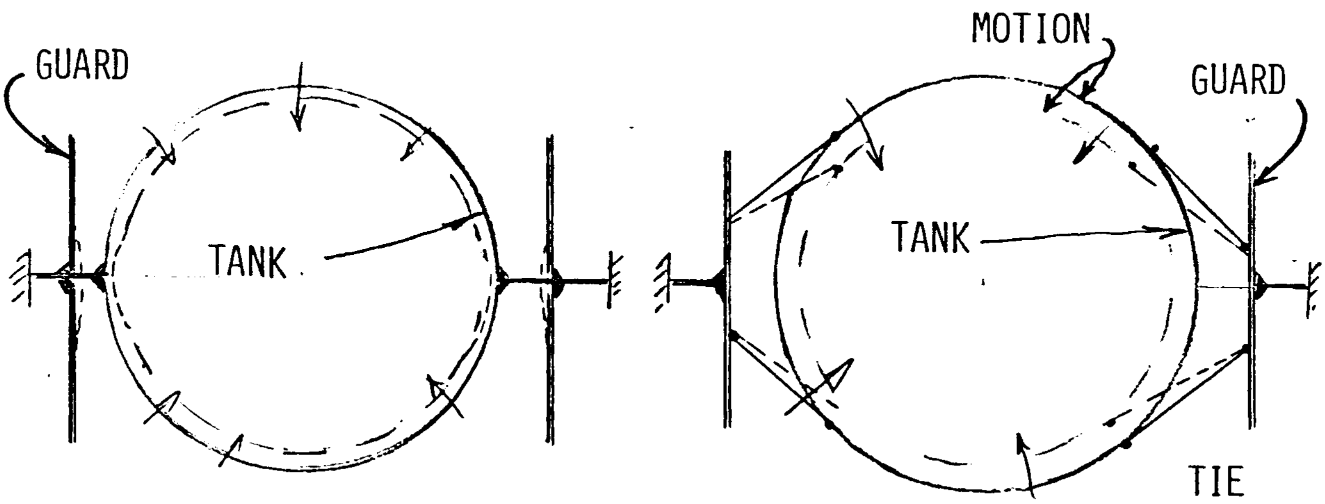
(b) IMPULSIVE (IMPACT) PRESSURE



(c) DISTRIBUTION (P.D.F.) OF IMPACT PRESSURE PEAKS (P).

Figure - 14

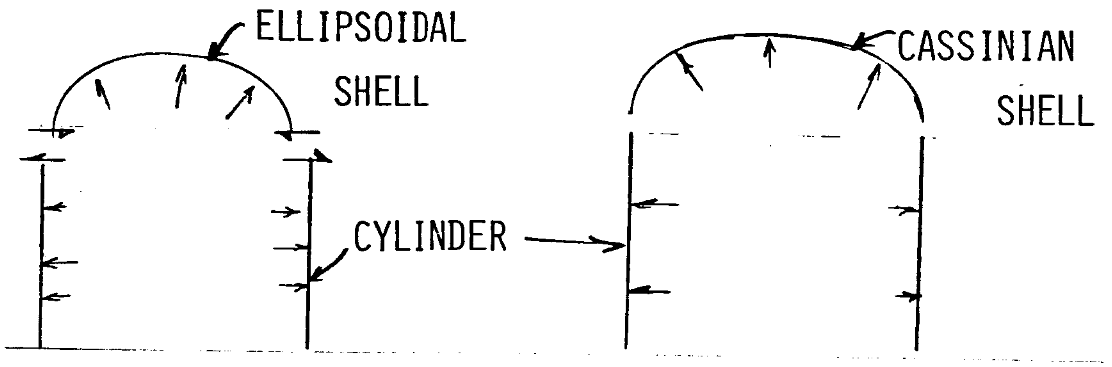
PROVIDE FOR DIFFERENTIAL PRESSURE, FORCES AND MOTION



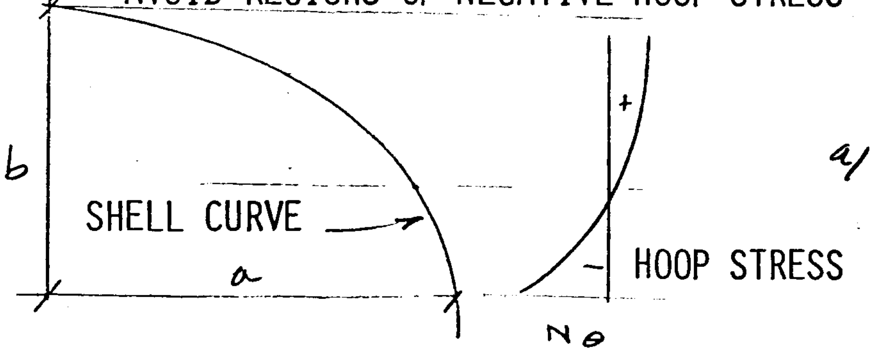
AVOID DIRECT RESTRAINT OF THERMAL AND PRESSURE MOTIONS

PROVIDE KINEMATIC SUPPORTS

AVOID DISCONTINUITY STRESSES AND FORCES



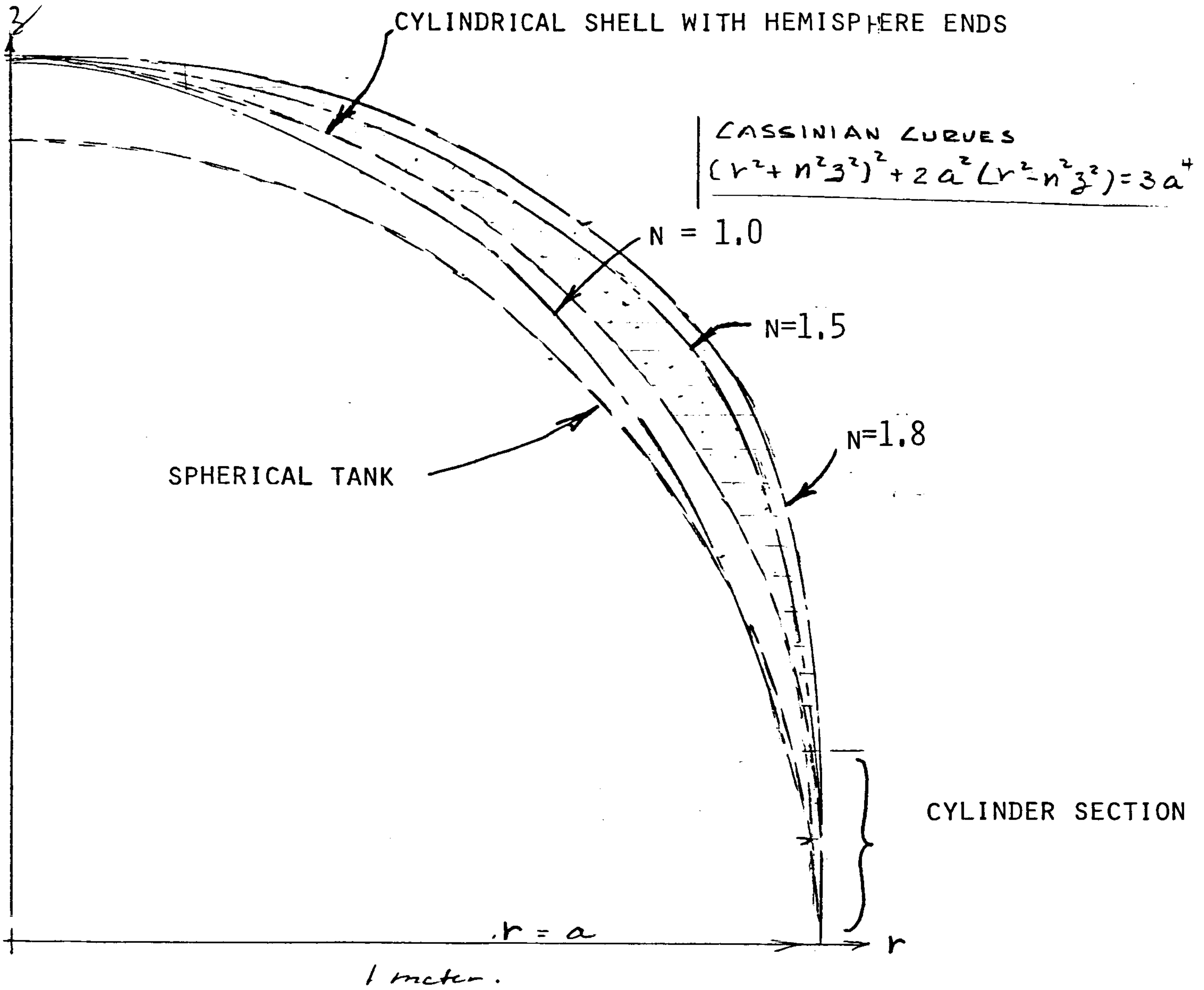
AVOID REGIONS OF NEGATIVE HOOP STRESS



$a/b < \sqrt{2}$

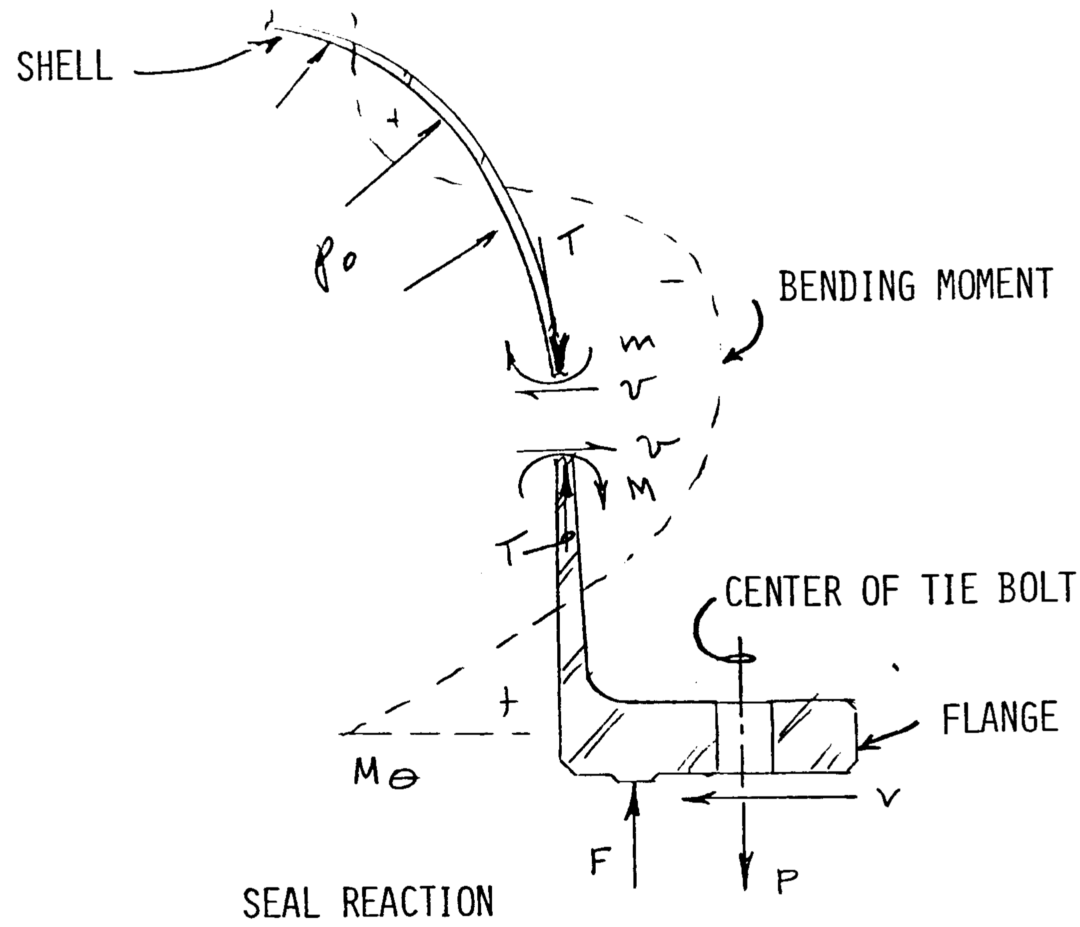
Figure - 15

OPTIMIZE SHELL SHAPES FOR PERFORMANCE

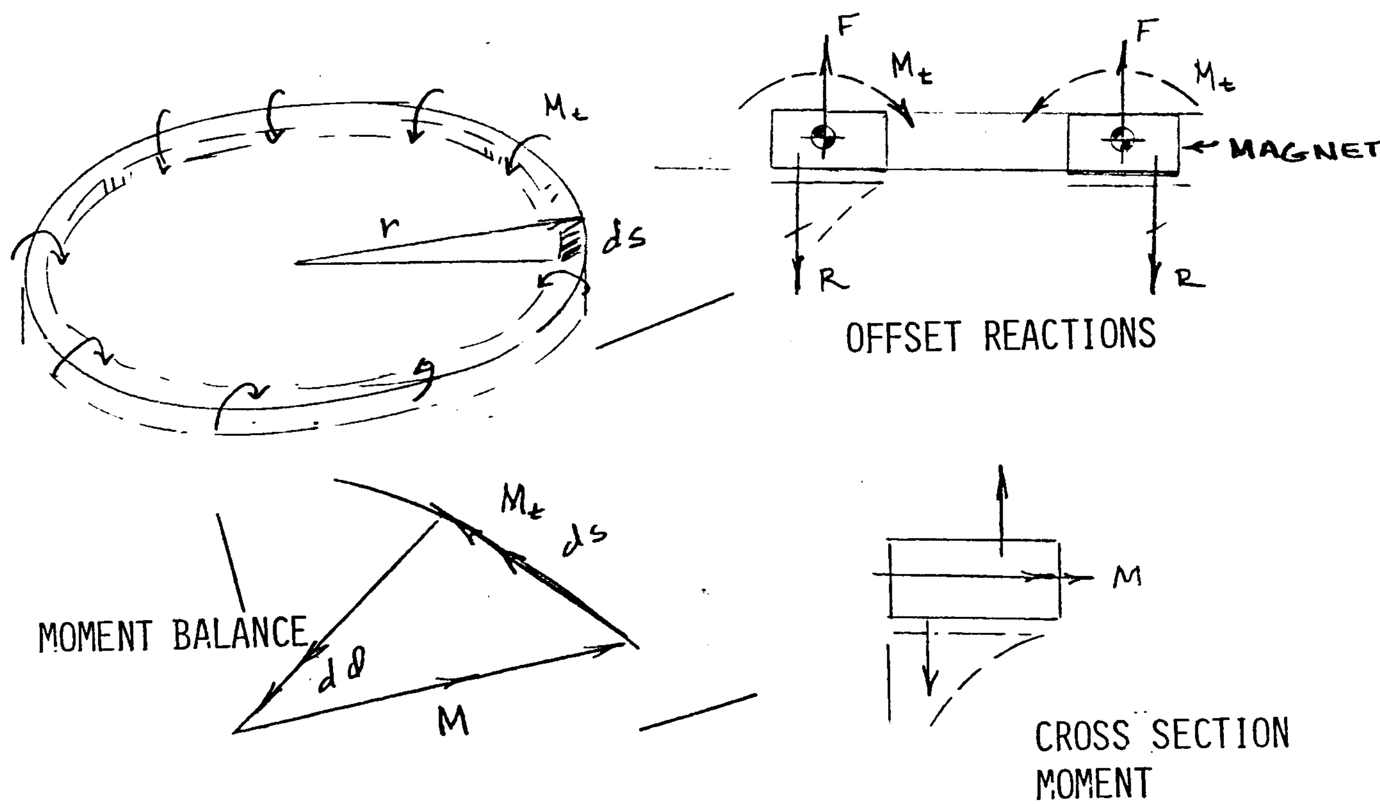


SHAPE MAY PROVIDE INCREASE OF 15% VOLUME OVER SPHERICAL SHAPE

Figure - 16

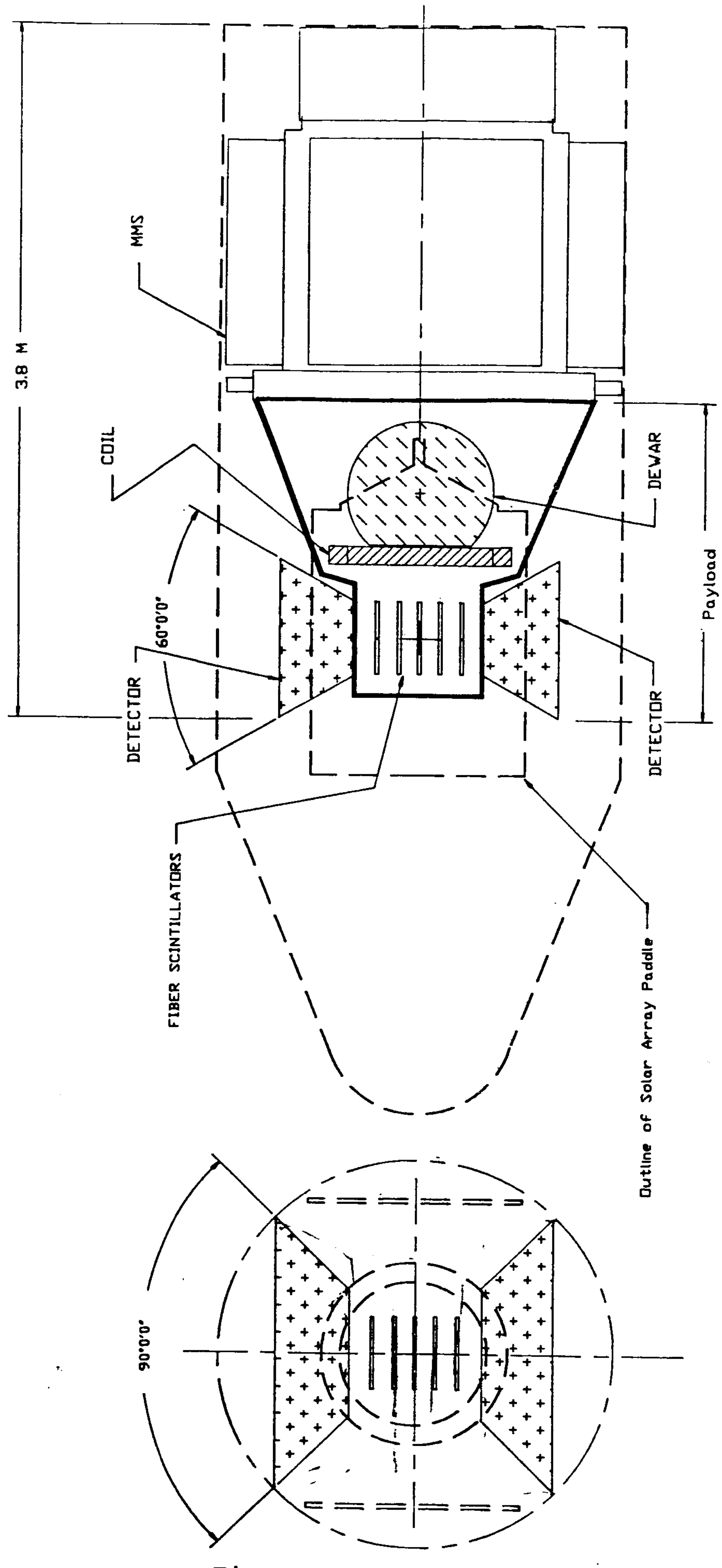


PROVIDE FOR PROPER SHELL ATTACHMENT DESIGN



DESIGN MAGNET TO WITHSTAND INDUCED MOMENT

Figure - 17



Astromag/Delta Concept

Figure - 18

Table - 1

IMPLIED STRUCTURAL REQUIREMENTS

PHYSICS REQUIREMENTS

- EXPERIMENT ARRANGEMENTS AND ATTACHMENTS
- WEIGHTS AND MATERIALS SELECTION
- SERVICING, INSPECTION, CHECK-OUT
- VOLUME OF HELIUM REQUIRED

SHUTTLE INTERFACE REQUIREMENTS

- LAUNCH AND LANDING STRUCTURAL INTEGRITY
- POWER AND DATA HANDLING REQUIREMENTS
- THERMAL CONTROL
- SERVICING

SPACE STATION INTERFACE

- ATTACHMENT
- SERVICING REQUIREMENTS
- DATA HANDLING INTERFACES
- IN-ORBIT HELIUM TRANSFER
- RESTRICTIONS BY OTHER EXPERIMENTS
- LIFE SAFETY

ENVIRONMENTAL REQUIREMENTS

- SHIPPING
- HANDLING
- TESTING
- STORAGE
- THERMAL CONTROL

Table - 2

SAFETY REQUIREMENTS

DEMONSTRATE FAIL-SAFE OPERATION, LAUNCH AND LANDING DESIGN

DEMONSTRATE PROPER FRACTURE CONTROL

DEMONSTRATE ANALYSIS AND TESTS OF PRESSURE VESSELS

PROVIDE CONTAINMENT OF FRACTURED PARTS

VERIFICATION OF ANALYSIS BY TESTS

TEST REQUIREMENTS

COMPONENT LEVEL TESTS

- RANDOM
- THERMAL
- STRUCTURAL LOADS
- DYNAMIC SIMULATION

SYSTEM'S LEVEL TESTS

- STEADY STATE LOAD SIMULATION
- THERMAL VACUUM TESTS
- MODEL VALIDATION TESTS
- LAUNCH ENVIRONMENT SIMULATION

FRACTURE ANALYSIS ASSUMPTIONS

- ALL STRUCTURAL ELEMENTS HAVE CRACKS -- DETERMINE UPPER BOUND IN SIZES
- ALL ELEMENTS MUST BE FAIL SAFE OR SAFE LIFE
  - FAIL SAFE = MISSION SUCCEEDS WITH FAILED PART
  - SAFE LIFE = LARGEST CRACK WILL NOT GROW TO FAILURE
- SOME MATERIALS WILL BE SUBJECTED TO STRESS CORROSION CRACKING
  - UNDER SUSTAINED LOADS
  - UNDER HARSH ENVIRONMENTS
- CRACK GROWTH DEPENDS ON
  - INITIAL SIZE AND GEOMETRY
  - FRACTURE TOUGHNESS OF MATERIAL
  - LOADING MAGNITUDE AND FREQUENCY
- BRITTLE MATERIALS AND PRESSURE VESSELS REQUIRE PROOF TESTS
  - DUE TO UNACCEPTABLE INITIAL CRACKS
  - CRACKS DIFFICULT TO DETECT
- NON-METALIC MATERIALS REQUIRE PROOF TESTS
  - DUE TO WIDE VARIATION IN PROPERTIES
  - INTERFACE PROPAGATION DIFFICULT TO PREDICT
- PROVIDE HYDROGEN EMBRITTLEMENT PROTECTION
- SEPARATION OF PARTS (.01 KG) IS CONSIDERED A CATASTROPHY
- ALL PRESSURE VESSELS ARE CONSIDERED FRACTURE CRITICAL

Table - 4

PRESSURE VESSEL DESIGN REQUIREMENTS

GENERAL : SHOW SHELL LEAKS BEFORE IT BURSTS

USE ONLY APPROVED MATERIALS MSFC SPEC 522A

ASME CODE METHOD

COMPLY WITH CODE

TEST A NON-FLIGHT UNIT TO 2 x NUMBER OF CYCLES

PROOF TEST FLIGHT UNIT TO 1.25 x MAX. OPERATING PRESSURE

FOR NON-COMPLIANCE WITH CODE DEMONSTRATE A FACTOR OF 4.0 ON BURST WITH A NON-FLIGHT UNIT.

MIL STD 1522 METHOD

STRESS ANALYSIS WITH SUPPORTING TEST AT 2 x MAX. PRESSURE (ACTUAL BURST MUST BE GREATER THAN 2 TIMES MEOP)

RUN LOAD CYCLE TESTS ON SECOND UNIT TO 2 TIMES LIFE CYCLES)

PROOF TEST FLIGHT UNIT TO 1.25 TIMES MEOF

NSS/HP-1740 METHOD

PROVIDE FRACTURE AND STRESS ANALYSIS

DEMONSTRATE AN ULTIMATE BURST OF 1.5 MEOF ON QUAL. UNIT

PROOF TEST FLIGHT UNIT 1.25 TIMES MEOF

FRACTURE MECHANICS LOAD CYCLES

ALL LEAK AND PROOF TEST CYCLES OF FLIGHT UNIT

ALL LIFE CYCLES

THERMAL CYCLES,

STRUCTURAL LAUNCH AND LANDING CYCLES (TIMES 4)

FRACTURE CONTROL PLAN

- DEVELOP ADEQUATE FRACTURE CONTROL PLAN AT OUTSET OF PROJECT
- PROVIDE RELIABLE DEFINITION OF ALL LOADS AND CYCLES
- PROVIDE DETAILED INTERNAL LOADS AND STRESSES
  DUE TO LOADS, THERMAL FORCES, ELECTROSTATIC FORCES
  MANUFACTURING PROCESSES, PRELOADS, PRESSURES, ETC.
- PROVIDE CAREFUL IDENTIFICATION OF ALL MATERIALS, ALLOYS PROCESSES ETC.
- PROVIDE A COMPREHENSIVE STRUCTURAL/STRESS ANALYSIS
- PROVIDE FORMAL CONFIGURATION CONTROL PROCEDURES
- VALIDATE ALL ANALYSIS THROUGH TEST PROGRAM
  SELECT TESTS CARFULLY
  DON'T OVERTEST FLIGHT UNITS (TESTS SHORTEN LIFE AND ARE SEVERE
- SCREEN ALL MANUFACTURING, HANDLING AND TESTS THROUGH INSPECTION
  AND QUALITY ASSURANCE CONTROLS
- REDUCE STRESS CONCENTRATIONS
- ELIMINATE RESIDUAL STRESSES IN MANUFACTURING PROCESS
- SELECT ONLY CRACK RESISTENT MATERIALS
- ASSURE ACCESS FOR INSPECTIONS
- PROVIDE TRANSIENT FLIGHT LOADS ANALYSIS UNDER ALL LOAD COMBINATIONS
- PROVIDE PART INSPECTIONS
- PROOF TEST ABOVE LEVEL OF FLIGHT LOADS
- USE SOFTWARE PROGRAMS TO QUALIFY BY ANALYSIS

RECOMMENDATIONS

PRIMARY STRUCTURAL MATERIALS

ALUMINUM 6061 T651
STAINLESS 300 SERIES

ULTIMATE LOAD FACTOR

12 GS APPLIED SIMULTANEOUSLY

COORDINATE SYSTEM FOR ANALYSIS

SHUTTLE COORDINATE SYSTEM

REQUIREMENTS

MATERIAL FACTORS

1.4 YIELD
1.8 ULTIMATE

SAFTY FACTOR

2.0 ANALYSIS

TYPES OF MODEL ANALYSIS

- o STRESS
- o FREQUENCY RESPONSE
- o MODAL RESPONSE
- o RANDOM RESPONSE
- o THERMAL
- o ACOUSTIC

STRUCTURAL MATERIALS SELECTION CONSIDERATIONS

- o OUT GASSING UNDER VACUUM
- o THERMAL COEFFICIENT OF EXPANSION
- o DENSITY
- o STRENGTH AT VARIOUS TEMPERATURES (ULTIMATE AND YIELD)
- o THERMAL EFFECTS
- o CREEP RESISTANCE
- o BRITTLE FRACTURE SENSITIVITY
- o CORROSION RESISTANCE
- o AVAILIBILITY
- o CONTROLABILITY (CERTIFICATION)

TYPICAL ACCEPTABLE FLIGHT STRUCTURAL MATERIALS

WELDABLE METALS

ALUMINUM 6061-T4 AND T6
" 6061-T651
" 5053
" 1100 SERIES
STAINLESS STEEL 300 SERIES

MACHINABLE METALS

ALUMINUM 2024-T3
TITANIUM T1-6A-4V
BERYLLIUM
MAGNESIUM

NONMETALS

FIBER GLASS

DYNAMIC DESIGN GOALS

FREQUENCY REQUIREMENT:

MAINTAIN FREQUENCIES ABOVE 20 HZ.

DE-COUPLE MAJOR MODES OF VIBRATION

STIFFEN LARGE EXPOSED AREAS

ATTENUATE HIGH FREQUENCY RESPONSE IN DELICATE ITEMS

PROVIDE NON-REDUNDANT SUPPORT FOR CRITICAL ALIGNMENT ITEMS

AVOID GAPPING OR SNUBBING IMPACTS

PROVIDE SUFFICIENT DYNAMIC ENVELOPES BETWEEN ELEMENTS

USE MATERIALS WITH HIGH DAMPING RATES

USE RUGGED COMPONENTS

VIBRATION ISOLATE DELICATE INSTRUMENTS

GEOMETRY GOALS

ENVELOPES

ESTABLISH SHUTTLE RESTRAINTS

ESTABLISH SPACE STATION CONSTRAINTS

ESTABLISH PHYSICS REQUIREMENTS FOR DETECTOR SIZES

ESTABLISH CURRENT TEST FACILITY GEOMETRY LIMITS

ESTABLISH FABRICATION LIMITS

SUPPORT STRUCTURE GEOMETRY

MINIMIZE LOAD PATH LENGTH

PROVIDE KINEMATIC SUPPORTS FOR DETERMINISTIC STRUCTURES

MAXIMIZE VOLUME OF LIQUID HELIUM SHELL

MINIMIZE PROXIMITY OF DETECTORS TO MAGNETS

MINIMIZE WEIGHT, STRESS AND DEFLECTIONS.

Table - 9

WEIGHT ESTIMATE FOR ASTROMAG GUARD VACUUM SHELL AND CRYOGEN TANK

ITEM	WEIGHT
GUARD SHELL	530 LBS
RINGS AND SUPPORT PADS	400 LBS
INNER CRYOGEN TANK	480 LBS
SHROUDS AND INSULATION	450 LBS
STRAPS (SUPPORT FOR TANK)	160 LBS
PLUMBING	120 LBS
MISC.	200 LBS

TOTAL WITHOUT HELIUM =	2340 LBS	(1100 KGS)
MAXIMUM LIQUID HELIUM		790 KGS
MAGNET COILS		1500 KGS
PERSISTENT SWITCH		100 KGS
SHUTTLE INTERFACE HARDWARE		320 KGS

TOTAL ESTIMATED WEIGHT = 3810 KGS